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Modular Dissolution Process

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Insinöörityön tavoitteena oli suunnitella modulaarinen liuotusyksikkö ja tutkia selluloosaderivaatan liuotusta kyseisessä prosessissa. Sen on oltava helposti liitettävissä jo valmiin viskoosiprosessin kehruulinjastoon ja saatava toimintakuntoiseksi tai irrotettua 24 tunnin kuluttua paikalle saapumisesta. Työssä tutkittiin etenkin sitä, miten ratkaisu muuttuu mittakaavan muuttuessa ja mitä on otettava huomioon konenormeissa ja ympäristödirektiiveissä.

Työssä tutustutaan selluloosakuitujen valmistuksen historiaan lyhyesti, sekä erääseen nykyaikaiseen menetelmään. Uusi menetelmä liittyy selluloosaderivaatan liuotukseen. Tälle uudelle menetelmälle on suunniteltu modulaarinen liuotusyksikkö merikelpoisen konttisysteemin sisälle, jotta sen kuljetus maailman ympäri on mahdollista.

Liuotusyksikköön kuuluvat ruuvikuljettimet ovat skaalattu sen mukaan, että saataisiin maksimi kapasiteetti sen suhteen, minkä kokoinen ruuvi mahtuu 40 jalkaa pitkän merikontin sisään muiden komponenttiensa kanssa. Skaalatusta prosessista on esitetty taseet ja virtauskaavio.

Skaalauksen jälkeen työssä on tehty kustannusarvio konttisysteemin suunnittelusta, rakentamaisesta ja siitä miten investointihinnat muuttuvat, kun kapasiteetti muuttuu. Konttisysteemi maksaa kokonaisuudessaan noin 1,5 miljoonaa euroa, mutta kustannukset vähenevät, jos prosessia varten tilataan useita liuotusyksiköitä.

Avainsanat	Selluloosaderivaatta, Liuotusyksikkö

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The objective of this Bachelor's thesis was to design a modular dissolution unit and research the dissolution of cellulose derivate in the process. It must be able to attach to or detach from an existing viscose process's spinning unit within 24 hours of arrival. The focus was especially on how the process and scaling changes when the process capacity changes and what must be taken into consideration in the Far East and EU machinery norms.

In this thesis a brief history of cellulose-based textile manufacture is explained, as well as the modern methods being developed. The new method is based on a derivative of cellulose and its dissolution. The modular dissolution unit consists of two screw extruders that are designed and scaled in a way that they fit inside sea-worthy containers that can be shipped around the world. The process is scaled to have the maximum capacity screws that can fit inside 40 feet long sea containers with all its other components such as electrical boxes and pumps. To aid the scaling process mass balance and flow diagrams are presented.

After scaling, cost vs. productivity was considered in terms of the design, manufacture, and the changes in the amount of investments when the process capacity changes. The container unit's starting price is 1.5 million euros, but the costs will decrease, if multiple units are ordered for the process.

Keywords	cellulose derivative, modular dissolution

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Symbol library

$A_{Segment}$	Area of segment [m^2]
A_{Sector}	Area of sector [m^2]
$A_{Triangle}$	Area of triangle [m^2]
α	90°
A_{AB}	Area of overlapping circles A and B [m^2]
r	Radius of screw element in screw extruder [m]
φ	Revolutions per second [1/s]
z	Fill stage
L	Screw length [m]
L_{pit}	Pitch length [m]
V	Screw channel volume [m^3]
$\dot{V}$	Volume flow [m^3/s]
τ	Residence time [s]
τ_{pit}	Pitch residence time [s]
V_{pit}	Pitch volume [m^3]
n_{pit}	Number of pitches
kDa	kiloDaltons molar mass of cellulose [1000 g/mole]

Abbreviations

IFC	Infinited Fiber Company Oy
VTT	Technical Research Centre of Finland
CCA	Cellulose carbamate
SAA	Solubility aiding agent
RPS	Revolutions per second
NaOH	Sodium hydroxide
CS_2	Carbon disulphide
CNC	Computerized numerical control

1 Introduction

Ever since clothing was first innovated by the humankind, we have developed ways to make them better, easier, and more efficiently. The most widely used methods today use extreme amounts of water. Cellulose fiber-based textiles mainly use cotton as raw material, and the agricultural needs for water are huge. During recent years there has been a growing shortage of cotton. 40 % of the worlds textiles are cotton and 55 % are synthetic [1]. It is possible that cotton is replaced in many applications with for example polyester. These synthetic fibers are fossil oil-based and release micro polymer pollution into the environment and their effect on health and environment are not yet completely understood [2]. More environmentally friendly methods for textile production have been developed, such as regenerated cellulose fibers. In this case, cellulose is dissolved, spun to fibre and regenerated to solid product such as viscose or lyocell. Infinited Fiber Company Oy has VTT's technology to produce cellulose derivative CCA from cotton waste materials such as old bedsheets.

The most widely used method for production of cellulose fibers is the xanthate method. This method is used to make various products, such as viscose and cellophane. The process starts with pulp that has high concentration of cellulose. Lignin must be removed because it is useless in the process. Sodium hydroxide is added to the pulp to form cellulose's sodium salt, after which the salt is brought to contact with carbon disulfide CS_2 to form cellulose xanthate. Cellulose xanthate can now be regenerated back into cellulose fibers by extruding it into a coagulation bath of dilute sulfuric acid. After extrusion the fiber is stretched to achieve a sufficient tensile strength. The stretching allows the amorphous cellulose molecules to rearrange into a more crystalline structure. [3;4]

However, because the xanthate method is relatively old and the carbon disulfide is a dangerous chemical [5]. The cellulose carbamate CCA method is a promising alternative for more efficient and safe production method for cellulose fibers. There are many benefits to this new method: All filtering, spinning, washing and stretching machinery in an existing xanthate-based factory can still be used without replacement. The process is built inside sea containers; thus it is very modular, and for the clients, it costs a fraction of the investment compared to a whole new stationary process; the process inside the

sea container is closed to the personnel in the factory and operated from the cloud to prevent spying and copying; and the CCA method does not use any carbon disulfide and is therefore a much safer method. CCA is soluble in the NaOH solution with the addition of a solubility aiding agent SAA [6]. After dissolution it can be spun with the old xanthate-based machinery into fibers and processed to textiles.

2 Cellulose fibers and dissolution of CCA

2.1 General

Humans have used cellulose for different applications since ancient times, for example natural fiber flax, hemp, and cotton from plant materials were applied for early forms of paper, textiles and clothing. Fractionation of cellulose from woody plants was invented more than two centuries ago, which led to attempts to create man-made fibers. Cellulose molecule (Figure 1) was discovered by the French chemist Ansleme Payen in 1838 and since then it has been used as a raw material for many polymers such as celluloid and nitrocellulose. [4]

Cellulose can be found virtually in every plant in nature. It is the world's largest renewable resource. Cotton is the purest form of cellulose in nature as it contains over 90 % cellulose. Wood usually contains 50 % or less cellulose and other natural polymers called lignin and hemicellulose [4]. Cellulose fibers from cotton are from 5-20 µm long and the fibers themselves consist from tinier fibrils that are very small strands of cellulose [4;7]. Purified cotton has a degree of polymerization of 1000-3000 [8].

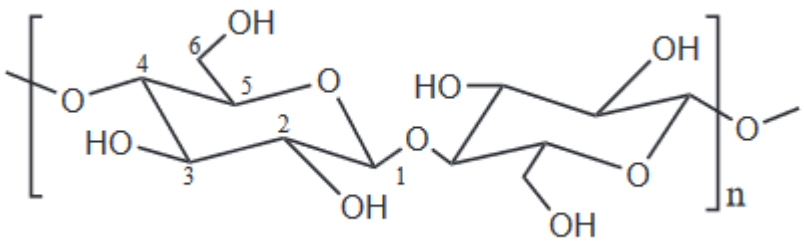


Figure 1. Molecular structure of cellulose [8].

Cellulose is not soluble in water because of the strong intramolecular hydrogen bonds and cross-linked cellulose molecules [4]. Fibers are particularly hard to dissolve because they have six layers in its structure that need to be penetrated [7].

The first layer is called the “cuticle” and it is the outermost layer of the fiber. It is waxy and protects the fiber. This layer does not contain cellulose but other biopolymers called pectins and proteinaceous materials. Converted and especially used textile fibers do not have cuticle due to mercerizing and consequential washing. Second layer is the “primary wall”. The primary wall is nearly pure cellulose and is the cell wall of the fiber and its structure is made of fibrils. The third layer is called “winding layer” and its structure differs from that of the other layers. The fibers in this layer form a netting type pattern. The largest portion of the fiber is called the “secondary wall”, it has parallel layers of cellulose fibrils that are packed tightly together. At the centre of the fiber is a layer called “lumen wall”, between the secondary wall and lumen. Inside the wall there is a hollow channel that during the growth serves the purpose of housing protoplast. Protoplast is all the material inside a living cell. Protoplast dries when the growth stops, leaving an open space inside the lumen wall (Figure 2). [7;9]

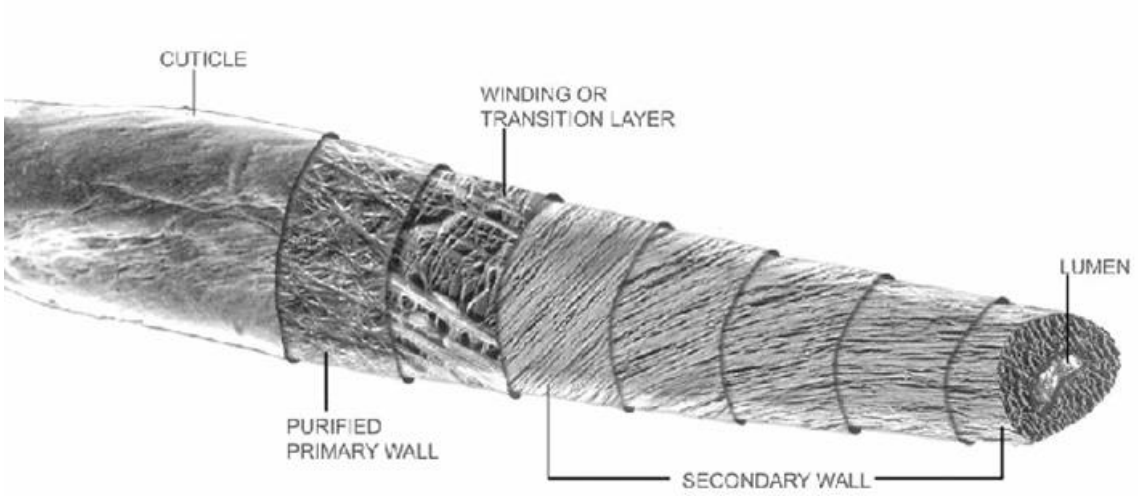


Figure 2. Structure of a cotton fiber [9].

2.2 Cellulose carbamate

Cellulose carbamate (Figure 3) is a derivative of cellulose that is easily soluble in an aqueous solution of sodium hydroxide at a low temperature, preferably less than -5 °C

[10]. Cellulose carbamate is produced from purified cellulose, for example, cotton or cotton textile waste materials by synthesis with urea [11]. CCA has a degree of polymerization from 250-350 kDa. It has been known for a while that this derivative of cellulose is soluble in aqueous NaOH; however, many challenges occur when the method is tried in a continuous, economical way.

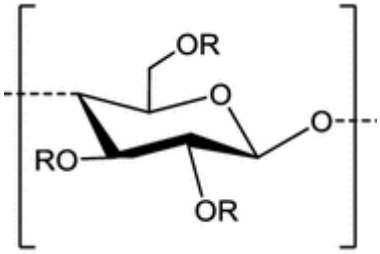


Figure 3. Molecular structure of cellulose carbamate [12].

In the molecular structure we can see that CCA resembles the basic cellulose monomer, but note that the three hydroxy groups have changed. R = -CO-NH_2 or H. [12]

2.3 Dissolution of cellulose carbamate

There have been several attempts at replacing the viscose method for a more ecological and safer method. The are many cons in the viscose method: the preparation of the spinning solution takes a long time and is dangerous; carbon disulphide is toxic, combustible and difficult to recover; CS_2 decomposes into H_2S which is also toxic; the cellulose xanthate product cannot be stored for reasonable amounts of time and must be put into further manufacture immediately. VTT has developed promising methods involving the cellulose derivative CCA and its spinning into fibers.

Since the discovery of CCA can be dissolved in NaOH solution, numerous methods for this have been tested. The older ones consisted of two dissolution steps: in the first step, the alkali solvent is more dilute than in the second step where the actual dissolution then happens. The dissolution time is only a few minutes in this method. However, if this process were to be implemented into an existing viscose plant, there would be only one concentration of sodium hydroxide readily and easily available. It would need to be either concentrated or diluted [10].

Another method for CCA dissolution, where a solubility aiding agent is used, has been developed by VTT. This method is ideal for continuous CCA dissolution, where no dilution or concentration of the alkali solvent is necessarily required. The method uses cooled solution of the readily available solution of NaOH from the factory and it is fed into both steps with same concentration, but at different flow rates. About 2/3 of the total NaOH flow is fed into the wetting step and the rest into the dissolution step. In the dissolution step a very small concentration (~1 m-%), of solubility aiding agent SAA is added to initiate the dissolving process. The CCA solution can be stored at below zero degrees Celsius for several days [6].

2.3.1 Wetting

Both wetting and the dissolution are done in a twin-screw extruder type dissolution process. Screw extruder is an excellent way to move fluids with high viscosity while simultaneously mixing it and keeping the residence time in an optimised window. The purpose of the wetting step is to prepare a suspension of CCA and aqueous NaOH solution for the actual dissolution in the second step. CCA is fed into the wetting step from a raw material container with a blower instrument. Cooled NaOH solution is pumped to the screw extruder and the suspension is mixed well with the revolving screw. The stream of the NaOH solution should be preferably about 2/3 the mass of the final solution in dissolution step. The screw must be long enough to achieve a sufficient residence time and mixing.

2.3.2 Dissolution

The dissolution step is also done in a twin-screw extruder. Now it is used to mix and dissolve the derivative. In this step a solubility aiding agent is added, along with the rest of the NaOH solution in a way that the composition of the stream is preferably: 6.5 m-% CCA; 8.5 m-% NaOH; and 1 m-% SAA. The addition of SAA enables nearly all the CCA to be dissolved. However, small portion of the CCA will not dissolve, the undissolved CCA becomes gelled, a thermodynamically more stable form that does not dissolve in these conditions. The gelled CCA needs to be filtered from the solution, luckily most of the old viscose factories have filtration units. [13]

The cellulose carbamate starts to lose nitrogen content while contacted with strong base. Typically, the released carbamate acid dissolves in the water, and neutralizes in the waste treatment. However, it is recommendable to use the solution soon when formed and not to store long times. [6]

2.3.3 Solubility aiding agent

It has been speculated that the effect of the SAA is based on local swelling in the fiber, where intermolecular hydrogen bonds are weakened and the dissolution can proceed further into the fiber. The swelling of the fiber depends on the size of the molecules in the solution used, a large heavy metal molecule in SAA solution decreases bond energy in the crystalline structure and finally breaks them, creating free cellulose molecules in the solution. [14]

The agent contains a heavy metal and is therefore harmful for the environment. There are various methods for removal of heavy metals form waste water, for example chemical precipitation with pH adjusting. This seems to be the most sensible way to proceed for this process, because the waste water solution needs pH adjusting nonetheless. Same methods are used in mining and water treatment plants in large sedimentation tanks. [15;16]

EU waste directive states that the manufacturer takes care of their waste by themselves or sends it to be taken care of by another waste disposal company. The producer also needs a competent authority's permit for waste disposal. The waste disposing process can not harm environment or human health or especially water systems, air, ground, plants, or animals. Required information for the authorities include: The amount and description of the waste, safety and precaution plans, methods for the process, quality control plans, and plans for the end of production. [17]

3 Process design and scaling

3.1 Containers

The process is designed to fit inside sea containers to ease the shipping of the process to the factories around the world. The most known and widely available containers come in two sizes: 40, and 20 feet long. Both containers are 8 feet wide and high [18]. The process is designed in 40 feet long containers because the process also requires large electrical components for running the system. The prices of sea containers vary considerably, mainly because of age. Container age has effect on the cargo-worthy of the container. Since the process might be in use for decades a completely new container is not a bad investment. Completely new 40 feet container would cost around 3800 € and a used one 1700 €. Insulation and refrigeration are not included in these prices. [19]

Since the process relies on low temperatures, insulation and refrigeration inside the container are necessary. Manufacturers build these in the standard 40 feet containers, they can cool the temperature inside the container to as low as -25 °C [19].

For the raw material, there are readily available systems for standard ISO shipping containers. CCA is produced into a powder and there are various methods for shipping powders. One promising method is the Caretex PE 1016 Fluidizing Jet-Flow liner, which can be installed into a standard ISO container and filled with the raw material. The unloading is simple, a truck picks up the container, tilts it, and unloads the payload with pneumatic systems. [20]

3.2 Screw geometry

To understand the dimension calculations for the process, a look into the geometry of the screw is needed. The screw is a helix-type solid and it can be thought to have a “packet” of volume between every pitch length (Figure 3), now referred to as pitch volume. During every revolution of the screw in a steady state, the screw pushes a volume equal to the pitch volume out of the extruder. With this information, an equation can be determined for the screw dimensions.

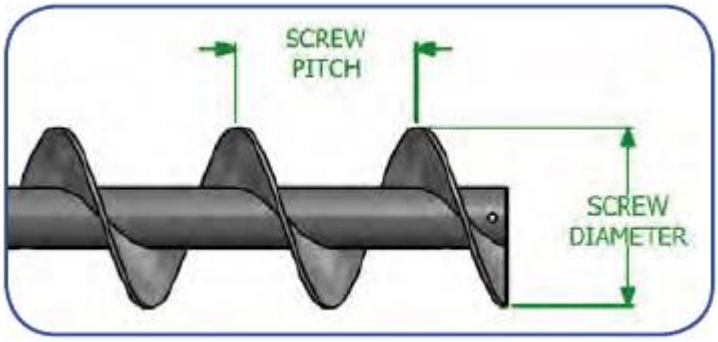


Figure 3. Basic screw design [21].

The process has two screws inside tube channels that overlap slightly. The cross section creates a shape that resembles binoculars. This shape is useful for calculating the pitch volume by multiplying the area of the shape with the pitch length.

The area of the overlapping circles (Figure 4) can be calculated by subtracting the area C from the area of two equal sized circles A and B, ($A_A = A_B$).

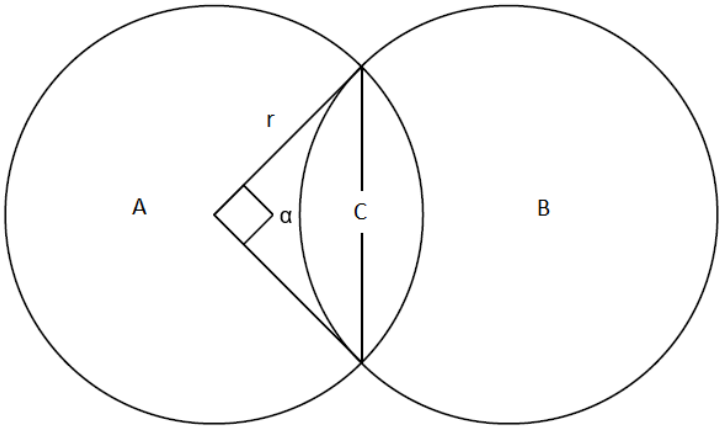


Figure 4. Two overlapping circles, cross section of twin-screw extruder channel.

Area C consists of two mirrored segments (Figure 5). Area of a segment can be calculated with Equation 1.

$$A_{Segment} = A_{Sector} - A_{Triangle}, \text{ if } 0° < \alpha \leq 180° \quad (1)\ [22]$$

$$A_{Triangle} = r*r/2, \text{ if } \alpha = 90° \quad (2)$$

$$A_{Sector} = \frac{\alpha}{360^o}\pi r^2 \quad (3)\ [22]$$

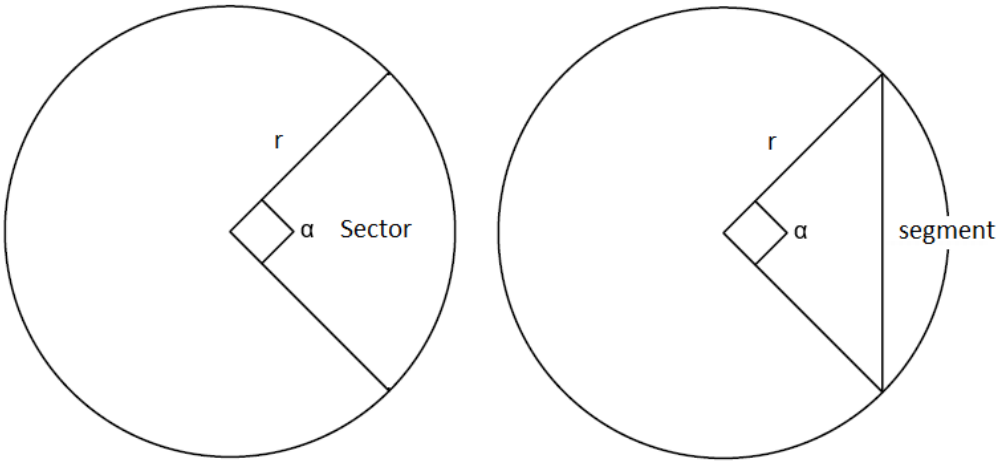


Figure 5. Areas of a sector and a segment inside a circle.

Now Equations (2) and (3) are input into Equation (1).

$$A_{Segment} = \frac{\alpha}{360^o}\pi r^2 - \frac{r^2}{2} \quad (4)$$

The area of the overlapping circles A and B can now be calculated with Equation 5, ($A_A = A_B$).

$$A_{AB} = 2A_A - 2A_{Segment} \quad (5)$$

$$A_{AB} = 2\pi r^2 - 2\left(\frac{\alpha}{360^o}\pi r^2 - \frac{r^2}{2}\right) \quad (5)$$

Since we know the revolving screw pushes a pitch volume out of the extruder every time it revolves, iterating a satisfying capacity for the process is now possible by trying different revolution speeds (RPS = φ). However, the screw should not be overfilled and a sufficient fill stage should be around 70 %. The fill stage is taken into consideration with symbol z in Equation 6.

$$Capacity = \varphi z L_{pit} A_{AB} \quad (6)$$

$$Capacity = \varphi z L_{pit}\left[2\pi r^2 - 2\left(\frac{\alpha}{360^o}\pi r^2 - \frac{r^2}{2}\right)\right] \quad (7)$$

3.3 Wetting screw dimensions

Screw diameter for wetting step was chosen to be 0.4 m and length 4 m with a pitch length of 0.025 m. The length is relatively large because the residence time needs to be quite long in order to get the CCA completely wet. Different RPS were tested in Microsoft Excel and with 0.50 RPS both capacity and residence time were excellent.

$$Capacity = 0.50\frac{1}{s} * 0.7 * 0.025m * \left\{2\pi * (0.20m)^2 - 2 * \left[\left(\frac{90^o}{360^o}\pi * (0.20m)^2\right) - \left(\frac{(0.20m)^2}{2}\right)\right]\right\} \approx 0.0019\frac{m^3}{s} \approx 7.20\frac{m^3}{h} \quad (7)$$

Local residence time in a single pitch can be calculated with pitch volume and capacity. Residence time in the whole wetting process can then be calculated by multiplying the local residence time in the pitch by the number of pitches.

$$V = \dot{V}\tau \quad (8)$$

$$V_{Pit} = \dot{V} * \tau_{Pit} \quad (8)$$

$$\tau_{Pit} = \frac{V_{Pit}}{\dot{V}} = \frac{L_{pit}zA_{AB}}{\varphi L_{pit}zA_{AB}} = \frac{1}{\varphi} \quad (9)$$

$$\tau_{Pit} = \frac{1}{0.50\frac{1}{s}} = 2.0s \quad (9)$$

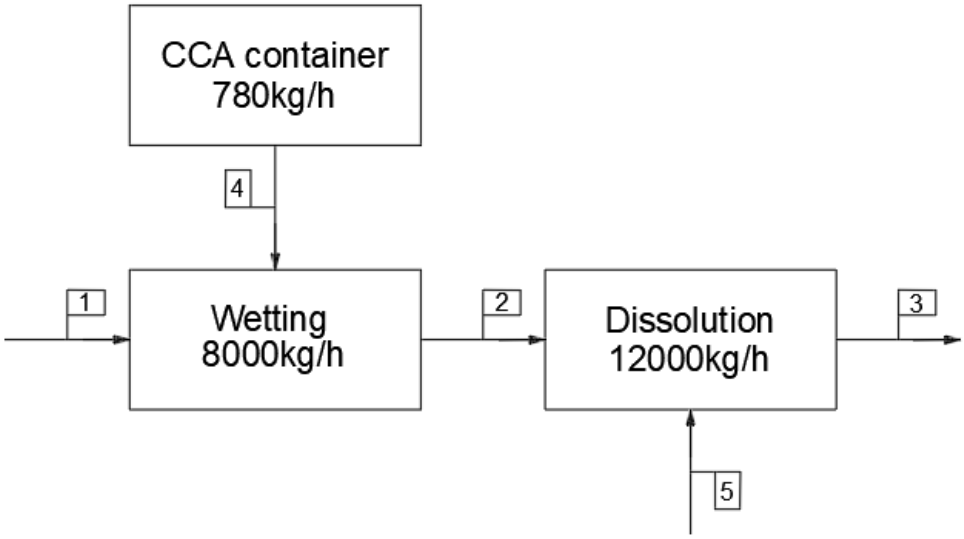
$$\tau = n_{pit}\tau_{pit} \quad (10), \text{ where } n_{pit} = \frac{L}{L_{pit}} \quad (11)$$

$$\tau = \frac{4m}{0.025m} * 2.0s \approx 320s \approx 5.3min \quad (10)$$

After iteration trials, a sufficient revolution speed for mixing and capacity was found. The screw specifications are listed below in Table 2 in chapter 7.

3.4 Dissolution screw dimensions

After the wetting step is designed, capacity for dissolution step can be determined with mass balance. Similarly, to the wetting screw calculations, the dimensions can be calculated by iterating Equation 7 with different RPS and find the capacity that was calculated from mass balance (Figure 6). CCA is easily dissolved with the aid of SAA and the total mass flow needed in this step is 12000 kg/h or 11.5 m^3/h as seen from the design mass balance.



Mass flows and compositions										
kg/h	1		2		3		4		5	
NaOH	613,7	0,085	613,7	0,077	1020	0,085	-	-	406,3	0,10
CCA	-	-	780	0,098	780	0,065	780	1	-	
SSA	-	-	-	-	120	0,01	-	-	120	0,03
H2O	6606,3	0,915	6606,3	0,826	10080	0,84	-	-	3473,7	0,87
TOTAL	7220	1	8000	1	12000	1	780	1	4000	1
Temperature (C°)	-10		-10		-10		20		-10	

Figure 6. Design mass balance stream compositions.

Iteration trials with different RPS in Equation 7 show that 0.80 RPS produces sufficient capacity and residence time in the dissolution screw. Screw length was decided to be 4 m long with a diameter of 0.4 m. The dimensions are the same as in wetting step to cut significantly designing and manufacturing costs. There is space for other appliances to

also fit inside the container next to the dissolution step, such as pumps. Full specifications for dissolution screw are in Table 3 in chapter 7.

$$Capacity = \varphi z L_{pit} A_{AB} \quad (6)$$

$$Capacity = 0.80\frac{1}{s} * 0.7 * 0.025m * \left\{2\pi * (0.20m)^2 - 2 * \left[\left(\frac{90^o}{360^o}\pi * (0.20m)^2\right) - \left(\frac{(0.20m)^2}{2}\right)\right]\right\} \approx 0.0032\frac{m^3}{s} \approx 11.52\frac{m^3}{h} \quad (6)$$

$$\tau = n_{pit}\tau_{pit} \quad (9)$$

$$\tau = \frac{4.0m}{0.025m} * \frac{1}{0.80\frac{1}{s}} \approx 200s \approx 3.33min \quad (9)$$

4 Linking to an existing factory

4.1 Linking order

The whole purpose of the sea container based method is to be able to quickly link to an existing viscose factory and replace the hazardous parts. The process must be running in 24 hours of the container arrival. In order to make this happen, careful planning needs to be done. Since there are practically limitless combinations on how the container setup can be done, the most basic one will be presented here. In reality the most efficient setup is discussed with the client.

The linking should start from the end, thus the dissolution container is the first part that is connected to the old factory. The dissolution container is connected to the filtration units and the electrical wiring and NaOH/SAA piping are connected to the container. The refrigeration inside the container can be started once power is on to save time from the ramp-up.

In this setup (Figure 7), wetting container is connected directly behind the dissolution container and similarly to the dissolution link, electrical and process piping can be attached. Refrigeration of this unit should also be started as soon as power is on.

Raw material container is located right on top of the wetting container to ease the raw material feed to the process with the blower instrument. The priority in raw material container linking, is to connect it to the ground to prevent static charge setting fire to the CCA, this could even trigger a dust explosion.

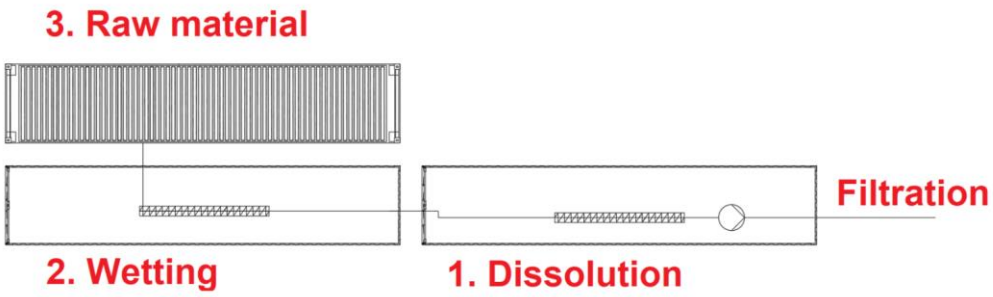


Figure 7. Linking order and the arrangement of the containers.

When the raw material container needs refilling, suggested method for the operation is the Caretex PE 1016 Fluidizing Jet-Flow liner system (Figure 9) which has been known to work well with powders. The operation starts by a truck backing up near the raw material container. The load on the truck is then tilted and pneumatically unloaded into the raw material container (Figure 8). [20]

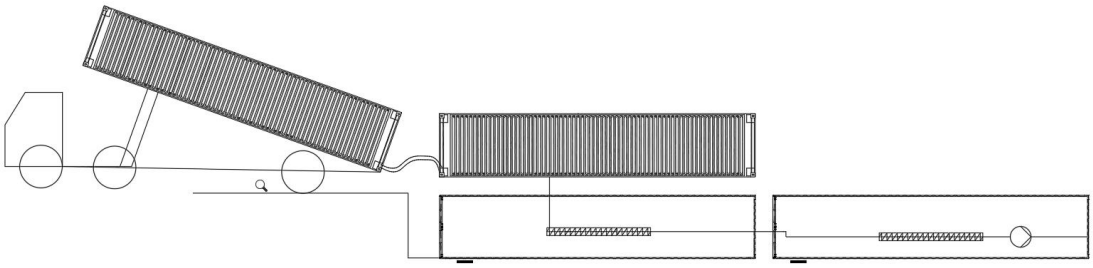


Figure 8. Unloading of the raw material.

Figure 9. Caretex PE 1016 Fluidizing Jet-Flow liner [20]

When every piece of the process is in place, the ramp-up can begin. The ramp-up operation should be started by starting to cool the NaOH solutions with heat exchangers and starting to feed them through the screws, while slowly bringing the revolution speeds of the screws up. The raw material feed can then begin to the wetting screw and thereafter to the dissolving screw. Samples should be taken from the output to find out when the consistency is right.

The beauty of the container setup is their ability to be stacked when the capacity of a single container unit might not seem much, they are built to meet the specifications of the client by putting multiple units next to, or even on top of each other to fulfil the client specifications.

4.2 Special requirements of the containers

For safe transportation, the containers need to be not only seaworthy but put together in a way where the centre of mass is in the middle of the container because safe lifting is not achieved otherwise. Suggested places for the screws are in the middle of the containers as seen in Figure 7, this leaves plenty of space for the screw pump and some electrical equipment needed to power and run the process from the cloud.

The container needs to be rigid, and withstand weights of many tons. The new refrigerated container weights 4.9 tons and can be loaded with 29 tons/m^2 [23]. The equipment inside the container weigh 4-5 tons, which means that the containers can be stacked

more than enough times; however, since the containers have spinning parts inside, maximum of 4 containers stacked is recommended to avoid tipping. The containers must withstand these conditions possibly for decades so reinforcing the corners with I-beams is a must.

5 Cost estimations

5.1 Sea containers

As mentioned above, a new sea-worthy container costs around 3800 € [19]. For the raw-material container this should be sufficient. The process, however, needs to be in cold temperatures and insulated. Scandic Container Oy sells refrigerated 40 feet containers at a reasonable price of 7300 € [23].

5.2 Process equipment

Twin-screw extruders that fit the specifications of this process are hard to find. A 0.4 m diameter screw extruder was manufactured for VTT in 1993 and it was worth 1M Finnish marks. Converted into euros and inflation considered, nowadays the price would be 250 k€ [24]. The dissolved CCA is pumped to the factory for spinning with a screw pump which costs about 12000 € [25].

5.3 Summary of cost estimations

The cost of a single container setup is estimated with aid from a chart from a book Plant Design and Economics for Chemical Engineers [26]. The estimations are based on the total price of the actual machines and the chart. Price per unit is estimated in Table 1 below.

The single unit was estimated to cost 1.5 M€. However, the larger the order the larger the manufacturing discounts are. More money will be saved, for example in legal fees and engineering that do not have to be made multiple times.

The extruder manufacture today is more automatic, efficient, and cheaper than before with modern CNC machinery, but the other parts in the machine are more advanced than before, such as computers and cooling jackets. This could affect the price today.

Table 1. Cost estimations of single container setup [26].

Object	Price (€)	percentage
40 ft container	4000	
40 ft container ref.	7300	
41 ft container ref.	7300	
Pump + heat ex.	70000	
Extruders 2x	500000	
Sum of machines	588600	40
workshop fee	120000	8
Piping	60000	4
Contractor	88000	6
Electrical equipment	74000	5
Wiring	60000	4
Engineering	206000	14
Service Facilities	147000	10
Construction	88000	6
Instrumentation + controls	44000	3
Sum / unit	1475600	100

6 Machinery directives and norms

The machinery used in the process must have a CE marking and the biggest problem with the machinery norms is to ensure that the machinery with CE markings must operate safely when two or more partly completed machines are linked together to form a machine. This requires a declaration of incorporation from the manufacturer or his authorised representative. This must be issued by the company that produces and/or assembles the machinery inside the sea container. [27]

If many machines or specific parts of the machine are designed to work together, they must be designed in a way that the stop controls including emergency stops can stop the machine and all the related equipment, if their continued operation is dangerous. [27]

Assembly instructions must contain an explanation of the conditions that must be fulfilled for the assembled machine to work without compromising health and safety of the operators. The instructions must be written in the language of the community using the machine and approved by the manufacturer or his approved representative. [27]

7 Research results

With the iteration trials, dimensions for both screws were specified. Designing the screws started with the idea of a single-screw type system, but it simply could not provide the necessary capacity that was needed, unless the screw diameter was unreasonably large. The single-screw method was then passed early in the development and switched to a twin-screw for both steps.

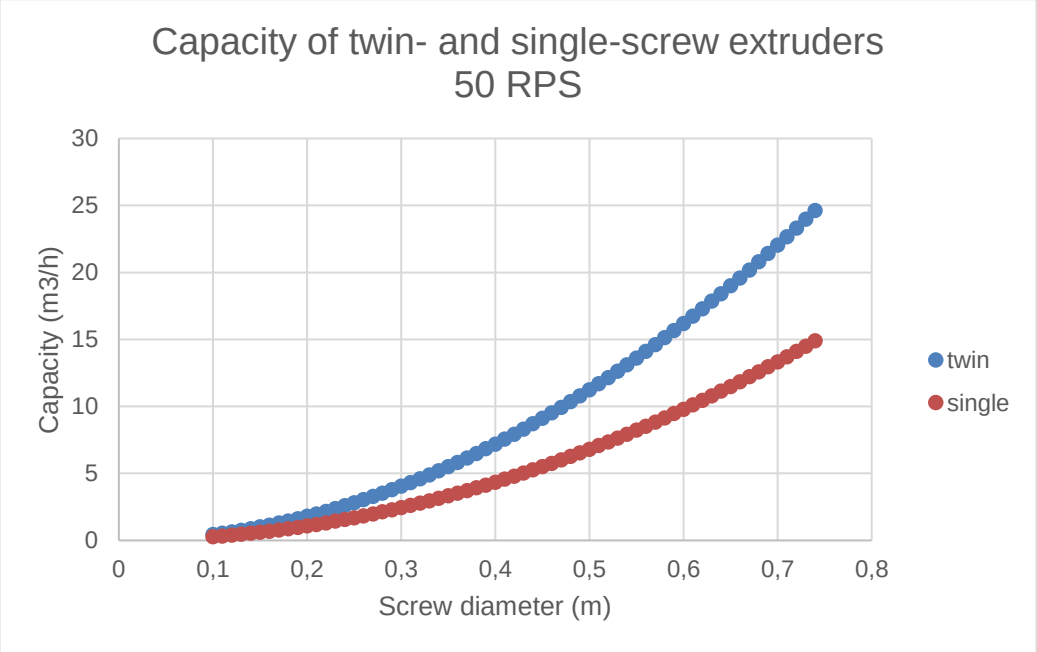


Figure 9. Capacity of twin- and single-screw extruders.

As seen from Figure 9, the capacity of the screw seems to nearly quadruple when the screw diameter doubles. Too large a diameter, however, is assumed to be too hard and expensive to manufacture. Also, the structural integrity of a huge diameter screw is questionable since they often are built hollow from the axel, and the forces directed to it are simply too large. Therefore a 0.4 m screw diameter was a safe candidate for this design, the figure is based on 0.5 RPS and 0.025 m pitch length. Flow diagrams for the process

are presented in Appendix 1, drawing symbols used are from PSK 3601 standard [28]. In the flow diagram, the flows have been down scaled by a factor of 0.80 from the design specifications to show a more realistic approach.

Another important factor in the screw design is the residence time; the faster the screw spins, the shorter the residence time. A balance in the revolution speed needed to be found for the screw to have good mixing capabilities, residence time, and capacity at the same time.

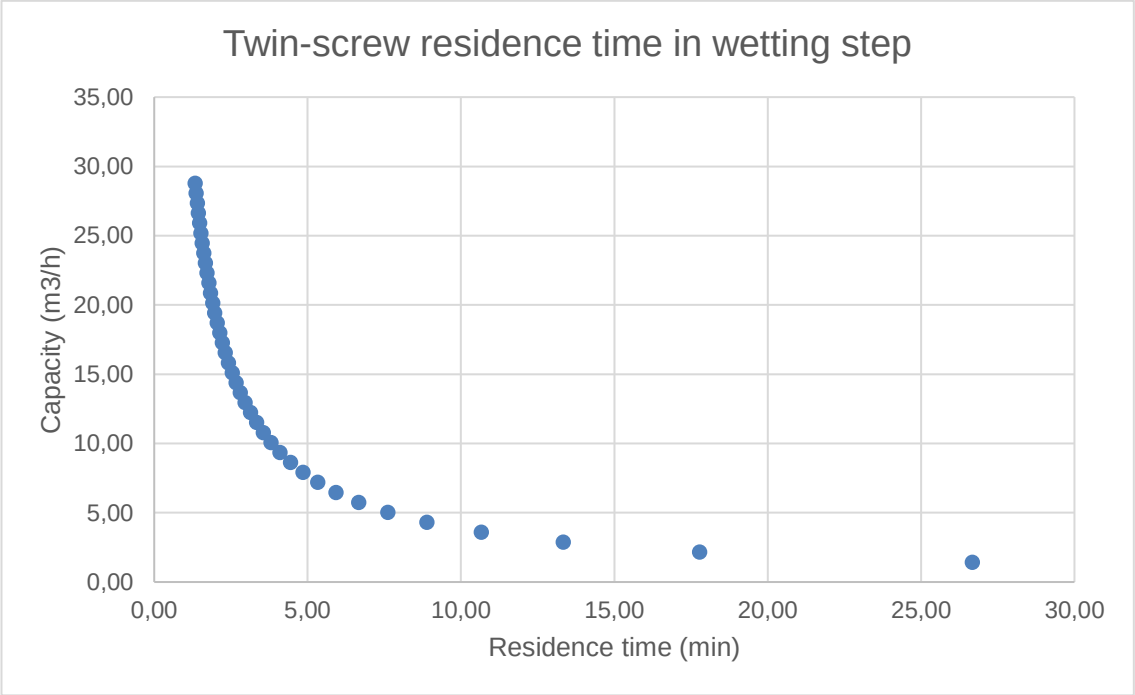


Figure 10. Residence time in wetting step.

Figure 10 shows that when capacity is raised by raising the revolution speed, the residence time drops drastically. Luckily, there is a residence time window of 5-10 minutes where the capacity is also excellent for these purposes. Iteration trial tables for wetting screw are presented in Appendix 2.

Table 2. Wetting screw design specifications.

Wetting screw specifications	
Length (m)	4
Diameter (m)	0.4
Pitch length (m)	0.025
Load rate (%)	70
Capacity (m3/h)	7.20
Residence time (min)	5.33
RPS (1/s)	0.50

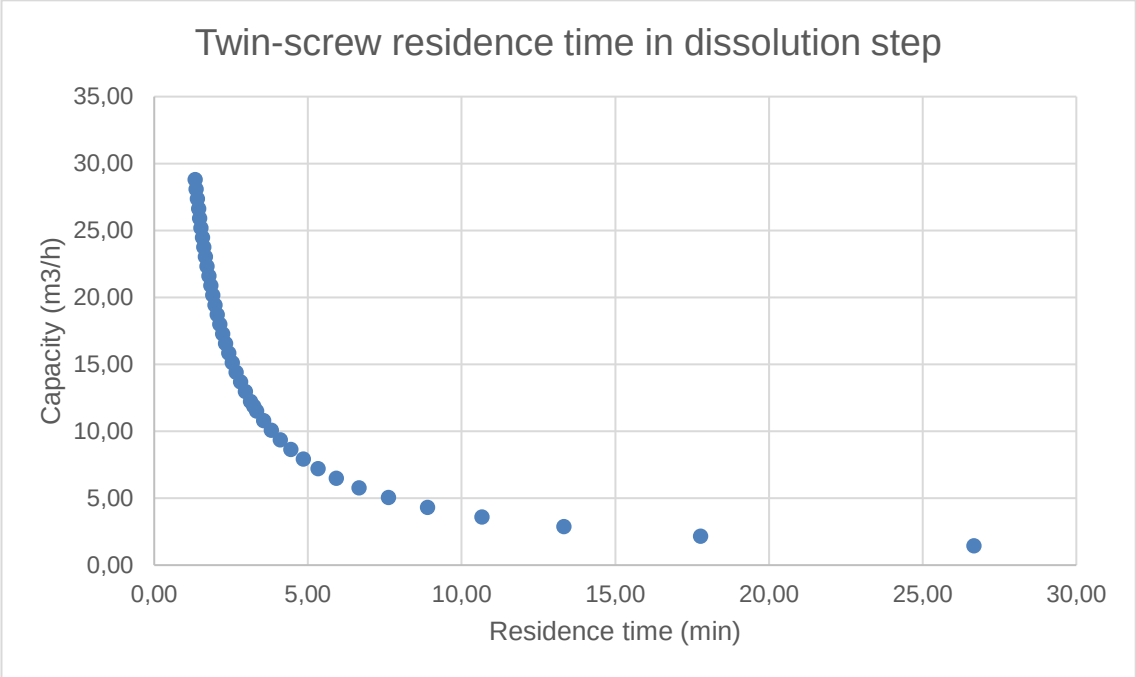


Figure 11. Residence time in dissolution step.

Similar results were found in the dissolution step, but it is worth noting that because the residence time does not need to be as long in the actual dissolution, a much larger capacity is easier to reach, therefore assisting in the mixing because the revolution speed can be higher. Iteration trial tables for dissolution screw are presented in Appendix 2.

Table 3. dissolution screw design specifications.

Dissolution screw specifications	
Length (m)	4
Diameter (m)	0.4
Pitch length (m)	0.025
Load rate (%)	70
Capacity (m3/h)	11.52
Residence time (min)	3.33
RPS (1/s)	0.80

8 Conclusions

8.1 Cost vs productivity

Productivity increases linearly with the number of production units but a larger order of production units will bring the manufacturing costs down. The limiting factor is the available space inside the factory. When containers no longer fit inside the factory, better and more compact technology needs to be researched and investments increase possibly even exponentially.

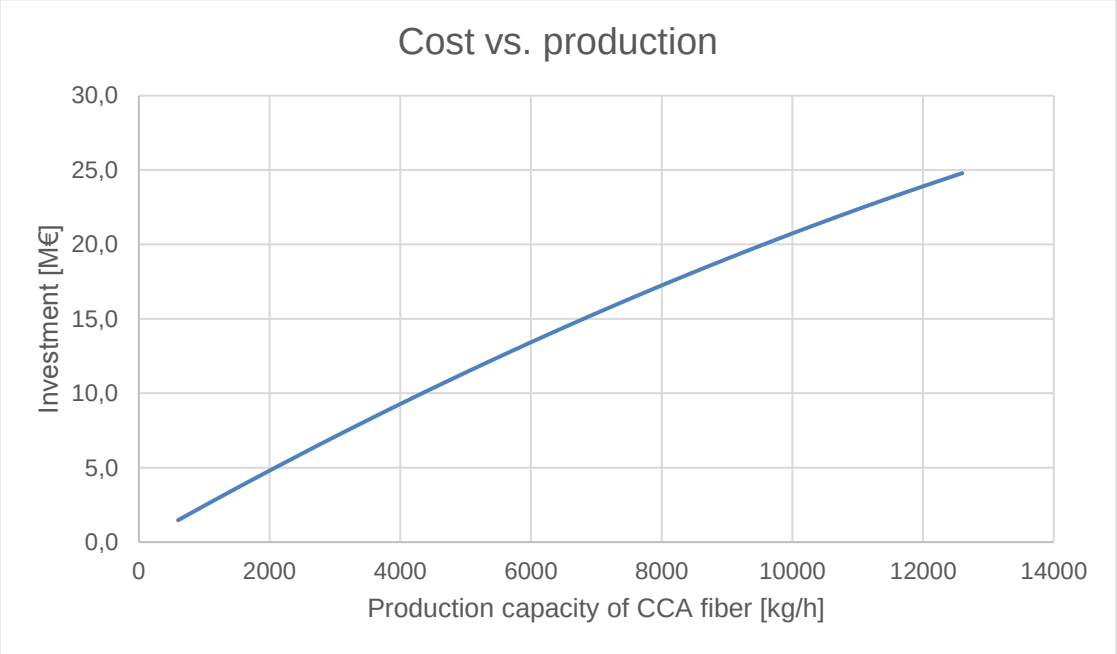


Figure 12. Cost vs. production of CCA solution with container method.

The cost of a container unit will decrease slightly if the order is large. One setup can produce roughly 600 kg of fiber per hour and the starting price is about 1.5 M€ per unit. Due to the excellent stacking capabilities of sea containers, different setups are easy to plan and efficient stack combination should be possible for any old viscose factory.

8.2 Limitations of a single production unit

Single production unit can produce 600 kg of CCA solution in an hour. This is not much in an industrial scale, and for a big factory only one production unit would not be an efficient investment unless it is an experimental trial or a leasing contract. For comparison, typical viscose factory produces around 2000 kg/h with one production line. Only one CCA unit is not able to compete with those numbers, but it is not far from that. With an estimated 6 M€ investment, a 2400 kg/h dissolution unit could be erected, which is a similar capacity to a generic production line in the industry.

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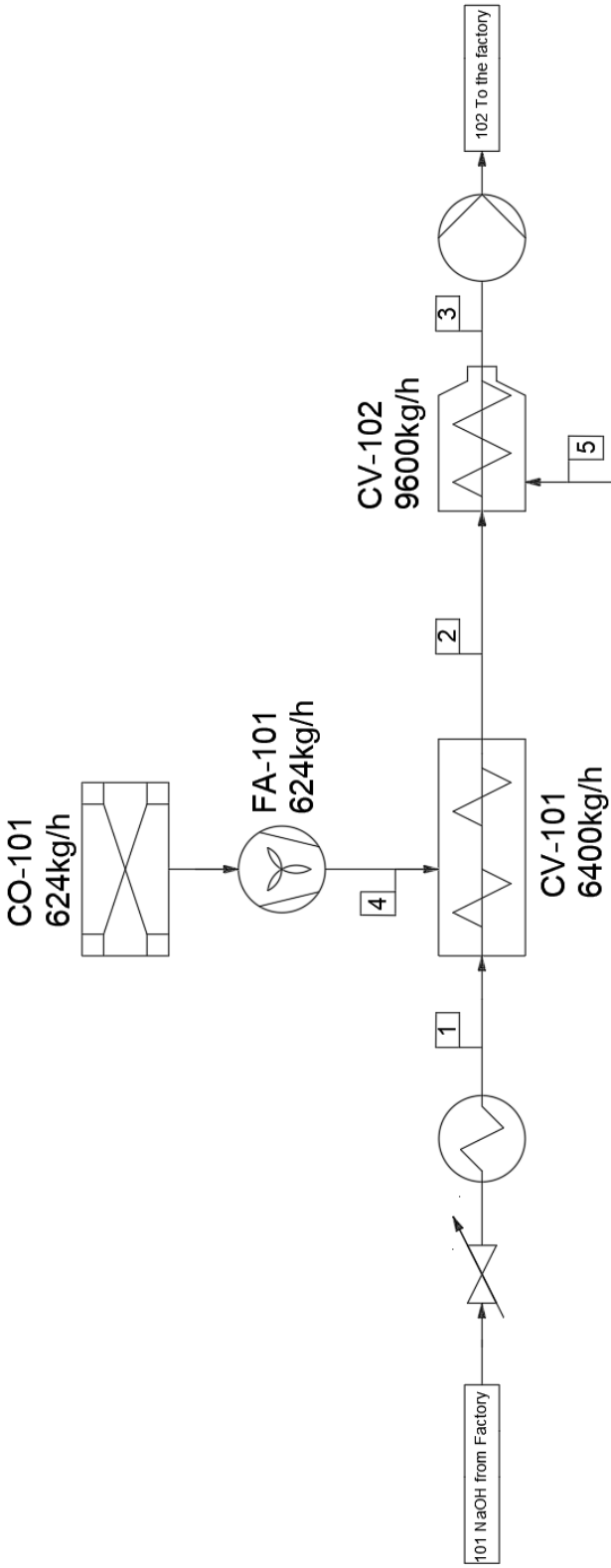
Appendix 1. Flow diagram



kg/h	1		2		3		4		5	
NaOH	490,96	0,085	490,96	0,077	816,00	0,085	-	-	325,04	0,10
CCA	-	-	624,00	0,098	624,00	0,065	624,00	1,00	-	
SSA	-	-	-	-	96,00	0,010	-	-	96,00	0,03
H2O	5285,04	0,915	5285,04	0,826	8064,00	0,840	-	-	2778,96	0,87
TOTAL	5776,00	1,000	6400,00	1	9600,00	1,000	624,00	1,00	3200,00	1,00
Temperature (C°)	-10,00		-10,00		-10,00		20,00		-10,00	

Appendix 2 Iteration tables

Wetting screw $Capacity = \varphi z L_{pit} A_{AB}$

RPS	capacity m3/h	tau pit (s)	residence time(min)
0.10	1.44	10.00	26.67
0.15	2.16	6.67	17.78
0.20	2.88	5.00	13.33
0.25	3.60	4.00	10.67
0.30	4.32	3.33	8.89
0.35	5.04	2.86	7.62
0.40	5.76	2.50	6.67
0.45	6.48	2.22	5.93
0.50	7.20	2.00	5.33
0.55	7.92	1.82	4.85
0.60	8.64	1.67	4.44
0.65	9.36	1.54	4.10
0.70	10.08	1.43	3.81
0.75	10.80	1.33	3.56
0.80	11.52	1.25	3.33
0.85	12.24	1.18	3.14
0.90	12.96	1.11	2.96
0.95	13.68	1.05	2.81
1.00	14.40	1.00	2.67
1.05	15.11	0.95	2.54
1.10	15.83	0.91	2.42
1.15	16.55	0.87	2.32
1.20	17.27	0.83	2.22
1.25	17.99	0.80	2.13
1.30	18.71	0.77	2.05
1.35	19.43	0.74	1.98
1.40	20.15	0.71	1.90
1.45	20.87	0.69	1.84
1.50	21.59	0.67	1.78
1.55	22.31	0.65	1.72
1.60	23.03	0.63	1.67
1.65	23.75	0.61	1.62
1.70	24.47	0.59	1.57
1.75	25.19	0.57	1.52
1.80	25.91	0.56	1.48
1.85	26.63	0.54	1.44
1.90	27.35	0.53	1.40
1.95	28.07	0.51	1.37
2.00	28.79	0.50	1.33

Dissolution screw $Capacity = \varphi z L_{pit} A_{AB}$

RPS	capacity m3/h	tau pit (s)	residence time(min)
0.10	1.44	10.00	26.67
0.15	2.16	6.67	17.78
0.20	2.88	5.00	13.33
0.25	3.60	4.00	10.67
0.30	4.32	3.33	8.89
0.35	5.04	2.86	7.62
0.40	5.76	2.50	6.67
0.45	6.48	2.22	5.93
0.50	7.20	2.00	5.33
0.55	7.92	1.82	4.85
0.60	8.64	1.67	4.44
0.65	9.36	1.54	4.10
0.70	10.08	1.43	3.81
0.75	10.80	1.33	3.56
0.80	11.52	1.25	3.33
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1.65	23.75	0.61	1.62
1.70	24.47	0.59	1.57
1.75	25.19	0.57	1.52
1.80	25.91	0.56	1.48
1.85	26.63	0.54	1.44
1.90	27.35	0.53	1.40
1.95	28.07	0.51	1.37
2.00	28.79	0.50	1.33